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Reduced risk estimations after remediation of lead (Pb) in drinking water at two US school districts

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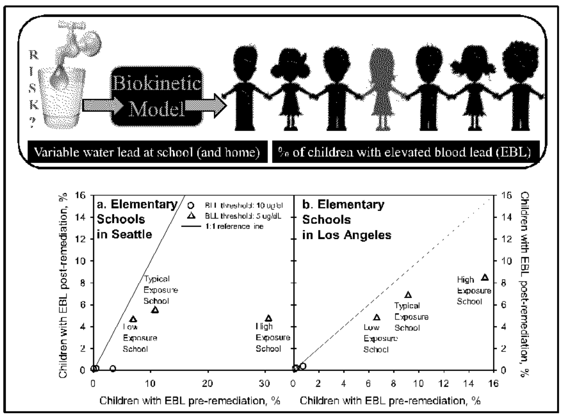
HIGHLIGHTS

- Risks after water Pb remediation at US schools were assessed for the first time.
- The entire measured water Pb distributions were input to the IEUBK model.
- The upper tail of the predicted blood Pb distribution reflects sensitive children (% at risk).
- This is a different approach from predictions of geometric mean blood Pb levels.

GRAPHICAL ABSTRACT



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abstract

The risk of students to develop elevated blood lead from drinking water consumption at schools was assessed, which is a different approach from predictions of geometric mean blood lead levels. Measured water lead levels (WLLs) from 63 elementary schools in Seattle and 601 elementary schools in Los Angeles were acquired before and after voluntary remediation of water lead contamination problems. Combined exposures to measured school WLLs (first-draw and flushed, 50% of water consumption) and home WLLs (50% of water consumption) were used as inputs to the Integrated Exposure Uptake Biokinetic (IEUBK) model for each school. In Seattle an average 11.2% of students were predicted to exceed a blood lead threshold of 5 μg/dL across 63 schools pre-remediation, but predicted risks at individual schools varied (7% risk of exceedance at a "low exposure school", 11% risk at a "typical exposure school", and 31% risk at a "high exposure school"). Addition of water filters and removal of lead plumbing lowered school WLL inputs to the model, and reduced the predicted risk output to 4.8% on average for Seattle elementary students across all 63 schools. The remnant post-remediation risk was attributable to other assumed background lead sources in the model (air, soil, dust, diet and home WLLs), with school WLLs practically eliminated as a health threat. Los Angeles schools instead instituted a flushing program which was assumed to eliminate first-draw WLLs as inputs to the model. With assumed benefits of remedial flushing, the predicted average risk of students to exceed a BLL threshold of 5 μg/dL dropped from 8.6% to 6.0% across 601 schools. In an era with increasingly stringent public health goals (e.g., reduction of blood lead safety threshold from 10 to 5 μg/dL), quantifiable health benefits to students were predicted after water lead remediation at two large US school systems.

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1. Introduction

1.1. Lead (Pb) contamination of school drinking water in the United States (US)

Drinking water at US schools may become contaminated from old leaded solder joints, old lead pipes and leaded brass/bronze fixtures, especially after prolonged periods of stagnation inside such leaded plumbing materials (after the end of the school day, over night, weekends, holidays and summer break).

Only the ~10% of US schools which are regulated as public water suppliers are subject to the federal Environmental Protection Agency (EPA) Lead and Copper Rule (LCR) of 1991 (Lambrinidou et al., 2010). The LCR has set a lead action level of 15 μg/L in 1 L first-draw water samples and requires water testing, remediation and public notification when exceeded (US EPA, 2006). Schools in 30 US states exceeded the LCR lead action level during 1998–2008 (Burke, 2009).

The remaining ~90% of US schools (classified as non-public water suppliers) are not subject to any mandatory water testing/remediation requirement, but instead rely on non-enforceable voluntary guidelines under the Lead Contamination Control Act (LCCA) of 1988 (Lambrinidou et al., 2010). These guidelines recommend that the water lead level (WLL) should not exceed 20 μg/L in any 250 mL first-draw sample from school water outlets (US EPA, 2006). Based on limited peer-reviewed literature or book chapters, schools in Pennsylvania (Bryant, 2004), Washington (Boyd et al., 2008), Missouri (Gnaedinger, 1993), California (Lambrinidou et al., 2010), Maryland (Lambrinidou et al., 2010), North Carolina (Maas et al., 1994), Iowa (Choquette and Gergely, 1992), New Jersey (Murphy, 1993), Kansas (Massey and Steele, 2012), Utah (Costa et al., 1997), and the District of Columbia (Lambrinidou et al., 2010) are known to have exceeded the LCCA recommendation of 20 μg/L lead in water.

Adding to that list is information from newspapers and television coverage (Lambrinidou et al., 2010) that indicated water lead problems in schools of 42 US states and the District of Columbia overall, at least once during 1988–2012. From these cases, Seattle Public Schools in Washington and Los Angeles Unified School District in California are two high profile public exemplars of voluntary water lead testing and remediation efforts.

1.2. Case study of Seattle Public Schools

Following parental inquiries in 2003, Seattle Public Schools (SPS) launched extensive water testing in all district schools in 2004, by collecting two 250-mL water samples from each drinking water outlet (fountains and sink faucets): 1) a first-draw sample after water had been standing overnight in the fountain and associated plumbing line, and 2) a flushed water sample after 30 s of subsequent flushing (Boyd et al., 2008). The 2004 test results for 71 SPS elementary schools showed that 19% of first-draw water samples and 3% of flushed samples had excessive lead (N20 μg/L) (Boyd et al., 2008) (Table 1). The local water utility met the federal lead regulation throughout the testing period (90th percentile WLL at home taps = 10.3 b 15 μg/L in 2004) (Seattle Public Utilities, 2012).

In a preliminary attempt to assess the public health impact, Sathyanarayana et al. (2006) predicted low blood lead levels (b 5 μg/dL) in 5–6 year old elementary students attending each SPS school, concluding that lead in water was not a health risk. While that work provided important initial insights to health effects, the authors acknowledged that it accounted for the 50th and 90th percentile WLL exposure only (not for the entire measured WLL distribution at each school), and it used the predicted geometric mean blood lead level of the exposed population as the sole criterion for the risk assessment. Other work recently predicted the risk of children to develop elevated blood lead (not just the geometric mean blood lead level) from variable water lead exposure at homes in the US (Edwards et al., 2009) and from constant water lead exposure at homes in Canada (Deshommes et al., 2013), but this approach has not yet been systematically applied to variable water lead exposure at schools.

SPS chose to voluntarily address the water lead contamination by implementing various remediation measures, including bottled water, filters, flushing outlets four times per year, and replacing pipes/bubbler heads. SPS also established a more stringent allowable lead action level of 10 μg/L (instead of 20 μg/L), and started requiring water testing, remediation and public notification every three years (Lambrinidou et al., 2010; Boyd et al., 2008). The latest follow-up testing of 2011–2012 showed that remediation measures were effective, but a new health risk assessment was not conducted (Table 1).

1.3. Case study of Los Angeles Unified School District

After parental inquiries and a local news station investigation, the Los Angeles Unified School District (LAUSD) undertook extensive sampling in its schools in 2008–2009, by collecting first-draw and flushed (after 30 s flushing) water samples from each water outlet. When combining 2008–2009 test results for the whole LAUSD district, 6.0% of first-draw water samples were found to release excessive lead (Table 1). In flushed water, 1.0% of samples released excessive lead in 2008–2009 (LAUSD, 2012) (Table 1). Similarly to the case of SPS, the local water utility was in compliance with the federal lead regulation when these LAUSD school taps were identified with excessive lead (90th percentile WLL at home taps = 10 μg/L in 2008 and 5.6 μg/L in 2009) (Los Angeles Department of Water and Power, 2012).

Due to budget constraints, LAUSD voluntarily committed to replacing fountains/pipes in only the worst-case schools, and relied on voluntary remedial morning flushing for 30 s in the majority of school water

Table 1
Summary of lead-in-water problems in Seattle Public Schools and in Los Angeles Unified School District in the last decade.

School system	Seattle Public Schools (SPS) in Seattle, WA	Los Angeles Unified School District (LAUSD) in Los Angeles, CA
Schools sampled	2004: 71 elementary schools	2008–2009: 629 elementary schools
School taps sampled	N ~ 3,100 overall	N ~ 51,000 overall
% school taps N US EPA guideline of 20 μg/L	2004: 19% of first-draw samples 3% of flushed samples (30 s)	2008–2009: 6% of first-draw samples 1% of flushed samples (30 s)
Range of lead detected	2004: b1–1,600 μg/L in a first-draw sample b1–370 μg/L in a flushed sample	2008–2009 0.2–13,000 μg/L in a first-draw sample 0.2–7,400 μg/L in a flushed sample
% school taps N 20 μg/L in latest follow-up testing after voluntary remediation	2011–2012: 1.0% of first-draw samples 0.2% of flushed samples (30 s)	2012: 6% of first-draw samples 1% of flushed samples (30 s)
Health risk assessment before/after remediation	Yes/No	No/No
References	Boyd et al. (2008); Lambrinidou et al. (2010); SPS (2012a,b); Sathyanarayana et al. (2006)	Lambrinidou et al. (2010); LAUSD (2012)

outlets to eliminate students' exposure to first-draw water lead (Lambrinidou et al., 2010). An assessment was never conducted to evaluate health impacts from lead exposure, either before or after implementation of the remedial flushing policy (Table 1).

1.4. Blood lead levels in children

The blood lead level (BLL) safety criterion for children was recently reduced from 10 to 5 μg/dL due to health concerns by the US Centers for Disease Control and Prevention (US CDC, 2012), while thresholds of 5 or even 1.2 μg/dL were also identified by the European Union (EU SCHER, 2011). The geometric mean BLL of surveyed children in the US is 1.0–1.5 μg/dL (depending on age), with 2.5% of surveyed children exceeding the new BLL reference value of 5 μg/dL (Brown and Margolis, 2012). To predict BLLs in children aged 0–7 years who have not been screened for blood lead, the US EPA developed the Integrated Exposure Uptake Biokinetic (IEUBK) model that accounts for cumulative exposure to several lead-contaminated media (US EPA, 2002).

The goal of this work was to estimate health risk before and after remediation of water lead contamination in SPS and LAUSD elementary school students (5–6 years old), by:

- compiling distributions of publicly available longitudinal WLLs (both first-draw and flushed water) before and after remediation,
- modeling the entire WLL distributions at each school, and
- using the IEUBK model to predict the percentage of students with BLL N 10 μg/dL and N5 μg/dL at each school before and after remediation, as a measure of the overall risk of elevated blood lead from school water.

This approach is different from conventional predictions of geometric mean BLLs in children. It accounts for:

- variability in WLLs as inputs to the model, and
- variability of individual children's BLL predictions from each WLL exposure scenario, as outputs of the model.

2. Materials and methods

2.1. School water lead data

To assess variability in school WLLs, extensive water lead testing results were needed. SPS and LAUSD are unique school districts with an abundance of publicly available water lead testing results from each school and each water outlet.

2.1.1. WLLs in Seattle Public Schools

Water lead data for SPS schools during 2004–2012 were obtained from the SPS website (SPS, 2012b). All SPS schools that exceeded the IEUBK model's age limit of 7 years-old were excluded, while specialty schools and multi-year schools that contained age groups below 7 years were included. Schools that were listed on the SPS website as closed, rental or temporary were not included in the dataset.

After this filtering process, 63 SPS elementary schools were included in the analysis, with first-draw and flushed WLLs from each bubbler and sink faucet at each school. WLLs (either first-draw or flushed) reported as b 1.0 μg/L were assigned a value of 0.5 μg/L (half the detection limit). In addition, each water outlet had to have coupled first and flushed WLL measurements for a given year. If either value was missing, the specific outlet was excluded from the analysis for that year. This resulted in the removal of 54 outlets from pre-remediation analysis (24 first-draw and 30 flushed WLLs were missing), and 21 outlets from post-remediation analysis (18 first-draw and 3 flushed WLLs were missing).

First-draw and flushed WLLs for each elementary school, and also for the school system as a whole (i.e., consolidated into a single dataset), were classified into two distinct time periods: pre-remediation and post-remediation. Distinction between pre- and post-remediation periods at each school was straightforward since the posted SPS WLL data were classified into different sampling phases that explained remediation stage. The pre-remediation period for each school was defined by the earliest available water lead testing round in that specific school. The post-remediation period was defined by the latest follow-up sampling round, after remediation was initiated in a specific SPS school.

As a result, initial sampling results at each school over the period March 2004 to August 2008 (depending on the school) were combined to form a pre-remediation distribution for SPS as a whole (N = 1418 for first-draw WLLs, N = 1418 for flushed WLLs). Final sampling at each school over the period July 2007 to April 2012 (depending on the school) was combined to form a post-remediation distribution for SPS as a whole (N = 2326 for first-draw WLLs, N = 2326 for flushed WLLs).

2.1.2. WLLs in Los Angeles Unified School District

Water lead data for LAUSD schools during 2008–2012 were acquired from personnel in the Office of Environmental Health and Safety (OEHS) at LAUSD, and underwent a filtering process similar to that for SPS. Early education centers located on school grounds were treated as separate schools (they were in different buildings and early education students were assumed to not use the main elementary buildings). A limited number of schools had less than 10 sampled water outlets and were removed from analysis, because the small sample size was considered inadequate to develop a representative WLL distribution for those schools.

After this filtering process, 601 LAUSD elementary schools were included in the analysis (LAUSD is a much larger school system than SPS). For every drinking water outlet (water bubblers and sink faucets) at each LAUSD school for a given year, coupled first-draw and flushed WLLs had to exist, or the outlet was excluded. If duplicate WLL values or testing existed for the same fountain for a given year, the highest value was chosen. In addition, limited paired first-draw/flushed WLLs reported as zero were removed, as these were below a feasible detection limit. This resulted in the removal of 371 first-draw WLLs and 352 flushed WLLs from analysis overall.

Unlike SPS, WLL data for more recent years were limited at LAUSD. Reported data decreased from 27,224 paired WLLs in 2008 down to just 21 in 2012. In addition, information about remediated schools and remediation timelines was unavailable, making it difficult to define distinct time periods of pre- and post-remediation. Based on these challenges, LAUSD was instead evaluated on their primary remediation method of flushing. This remediation method involves manually flushing all drinking water outlets for 30 s at the beginning of each school day. A pre-remediation scenario therefore accounted for both first-draw WLLs (N = 50336) and flushed WLLs (N = 50336) during 2008–2012, while a post-remediation scenario was defined only by flushed WLLs (N = 50336) during 2008–2012. Given that one flushing event may not keep WLLs consistently low throughout the school day (Barn and Kosatsky, 2011; Murphy, 1993), this analysis provides a "best case" estimation of flushing effectiveness.

2.2. IEUBK model

The IEUBK model (Win32 version 1.1 build 11) was downloaded on 2/15/2011 from the US EPA website at http://www.epa.gov/superfund/lead/products.htm The IEUBK model has been independently calibrated and empirically validated for blood lead levels below 30 μg/dL (e.g., Zaragoza and Hogan, 1998). A detailed discussion on model calibration and evaluation is available elsewhere (US EPA, 2006). The model combines four interrelated components to predict children's BLLs, including (1) exposure component, (2) uptake component, (3) biokinetic component, and (4) probability distribution component (Fig. 1).

The first three biological components allow prediction of a single value as the BLL. The fourth statistical component allows predicting a distribution of BLLs around the predicted geometric mean BLL, to

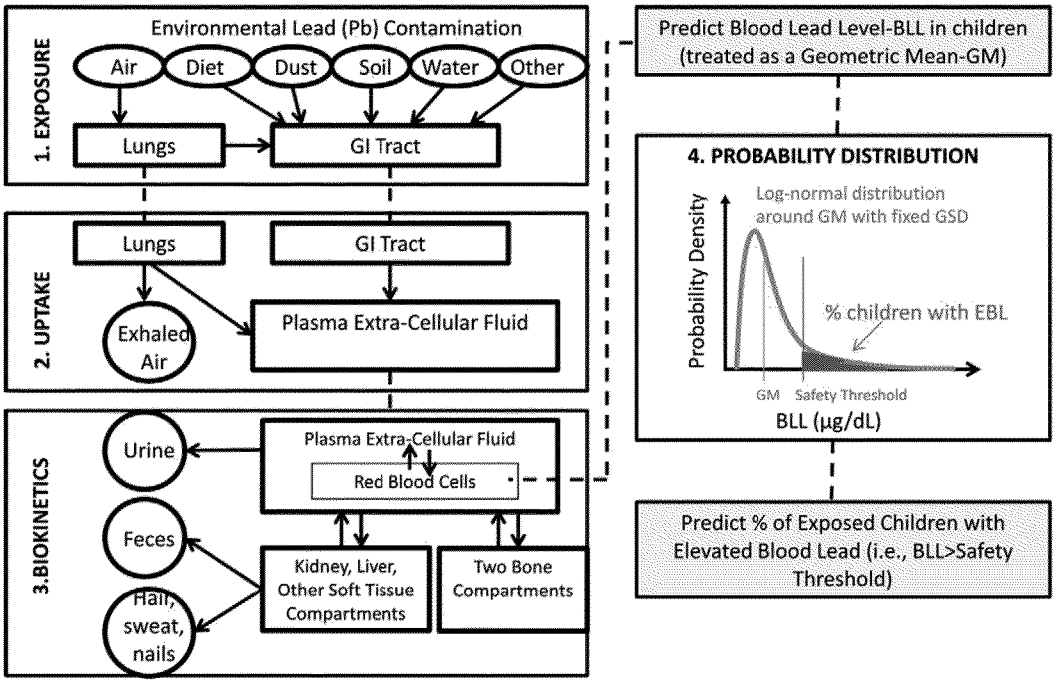

Fig. 1. Simplified structure of the US EPA IEUBK model for lead in children. Expanded from US EPA (2002). GI: gastrointestinal, BLL: blood lead level, GM: geometric mean, GSD: geometric standard deviation, EBL: elevated blood lead.

account for differences in behavior and individual lead uptake/ biokinetic patterns. From this distribution, the model can then estimate the percent of children who will exceed a chosen BLL safety threshold for a given lead exposure scenario. Prior work by Sathyanarayana et al. (2006) did not use the output of the probability distribution component, and only predicted geometric mean BLLs in Seattle students.

A hypothetical exposure of 5–6 year-old children to WLL of 20 μg/L predicts a geometric mean BLL of 3.6 μg/dL. But for an entire population of exposed children, IEUBK also predicts that 1.6% of that population would develop BLL N 10 μg/dL, and 25% of children would develop BLL N 5 μg/dL (Fig. 2), based on a geometric standard deviation of 1.6 μg/dL. Therefore, although the voluntary 20 μg/L lead limit for school fountains is not predicted to cause BLL N 5 μg/dL for a typical 5–6 year-old child (as expressed by the relatively low geometric mean BLL of 3.6 μg/dL b 5 μg/dL), it is predicted to cause BLL N 5 μg/dL for the upper 25% of a children's population who are more sensitive than

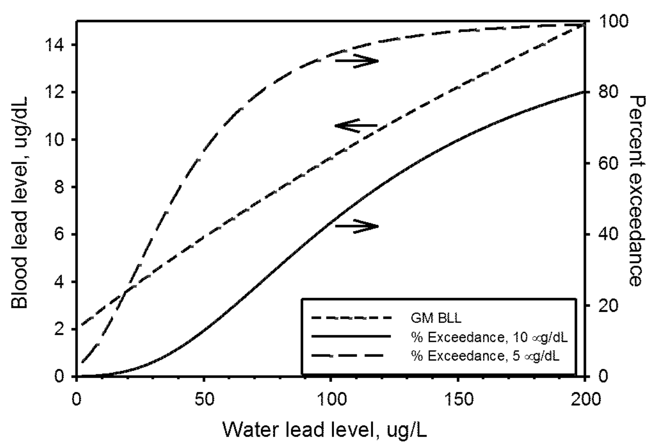

Fig. 2. Representative IEUBK model outputs, for hypothetical exposure of 5–6 year-old children to WLLs ranging from 0 to 200 μg/L for all water consumed. All other background lead exposures were fixed at their model default values. GM BLL: geometric mean blood lead level.

the typical child, when assuming that all other background lead exposures are fixed at their model default values. Based on these defaults, if the WLL was set to 0 μg/L, the resulting percent exceedances would be much lower at 2.8% and 0.04% for 5 and 10 μg/dL BLL thresholds respectively (Fig. 2).

2.3. Adapted IEUBK model

The source code for an earlier IEUBK model version of 0.99d was available at http://www.epa.gov/superfund/lead/products/srdappd.pdf (Appendix D of document System Requirements and Design for IEUBK model for Lead in Children). The model was re-coded in the statistical language R (R Development Core Team, 2010) for ease of multi-school analysis. The R code was validated against the US EPA model version for a variety of hypothetical exposure scenarios and then used for predictions throughout this work.

2.4. Model inputs

2.4.1. Combined WLL distributions as inputs to the model

Children consume water both at home and at school. First-draw water samples at school aim to capture lead exposure at the beginning of the school day, after the water has been left stagnant inside the piping overnight. Water samples collected after 30 s of flushing the plumbing are believed to represent more typical water lead exposure of students throughout the school day.

Monitored school first-draw and flushed WLLs were combined with assumed home WLLs, using the prior approach of Sathyanarayana et al. (2006). That is, 50% of children's daily water was assumed to be consumed at school (comprising of 25% first-draw water and 75% flushed water, as measured at a given school). Similar to the assumption of Sathyanarayana et al. (2006), the remaining 50% daily water was consumed at home and was assumed to be fixed at the 90th percentile WLL measured in Seattle or Los Angeles homes by the respective drinking water utilities (for Seattle 2004 (pre-remediation): 10.3 μg/L, 2010–2011 (post-remediation): 5 μg/L; for Los Angeles 2008: 10 μg/L, 2009–2011: 5.6 μg/L) (Seattle Public Utilities, 2012; Los Angeles Department of Water and Power, 2012). Aside from the 90th percentile WLL at homes that local drinking water utilities are required to report under the LCR, no other information was publicly available on home WLL exposure in Seattle and in Los Angeles.

Accounting for water lead exposure at home and at school created a combined WLL distribution for students of each school before and after remediation, based on the following formula:

$$\begin{aligned} WLL_{combined} &= WLL_{school} + WLL_{home} \\ WLL_{combined} &= 0.5(25\% \cdot WLL_{firstdraw} + 75\% \cdot WLL_{flushed}) \\ &\quad + 0.5\left(WLL_{90th\ percentile}\right). \end{aligned} \tag{1}$$

Eq. (1) was used to define WLL distributions at SPS schools before and after remediation, and at LAUSD schools before remediation. Since LAUSD remediation was mainly based on flushing which aimed to eliminate the high first-draw lead levels, the post-remediation WLL distribution at each LAUSD school was based on the following modified formula:

$$\begin{aligned} WLL_{combined} &= WLL_{school} + WLL_{home} \\ WLL_{combined} &= 0.5(WLL_{flushed}) + 0.5\left(WLL_{90th\ percentile}\right). \end{aligned} \tag{2}$$

2.4.2. Other lead exposures as inputs to the model

Because other environmental media aside from water were not the primary focus of this study, constant model default values were used to represent constant lead levels in those environmental media (US EPA, 2002): outdoor air at 0.10 μg/m^3 (indoor air at 30% of outdoor air), outdoor soil at 200 μg/g, indoor dust at 200 μg/g, and dietary intake at 2.05 μg/day (corresponding to 5–6 year-olds).

2.5. Model outputs and overall methodology

From each combined WLL distribution (created using Eqs. (1) or (2)), 19 percentiles of WLL values were selected to represent that distribution. For each school, the 19 representative percentiles of WLL values from the combined WLL distribution were run one-by-one through the IEUBK model, and the corresponding geometric mean BLL output was recorded. Based on the predicted geometric mean, log-normal distribution assumption, and assumed geometric standard deviation in the IEUBK model (GSD of 1.6 μg/dL), the percent of the exposed student population exceeding a given BLL threshold at each WLL could also be calculated by the IEUBK model (see Fig. 1). The percentage of exposed children's population exceeding a BLL threshold for the range of WLLs could then be plotted. By numerically integrating the area under each curve over the entire distribution of WLLs, the overall predicted risk of EBL for the students at a given school could be calculated.

The approach herein additionally ensures that the whole distribution of WLLs at a given school is accounted for. It essentially assumes that the same students consume water from the same tap on a daily basis, and that each tap at the school has a proportional percentage of the school population drinking from it. In other words, if there were 10 taps in the school, 10% of the school population is assumed to consistently drink water from each fountain.

2.5.1. Age

5–6 year-old children are the youngest in the IEUBK model range (0–7 years) who attend elementary school, and this age group was used for all model simulations. The default daily water consumption for this age group is set at 0.58 L/day in the IEUBK model, and this daily water consumption was used for all simulations.

3. Results and discussion

3.1. WLL variability in SPS and LAUSD school districts pre- and post-remediation

Individual school WLLs were consolidated into single datasets for each school district as a whole, to obtain useful information on (1) the extent and magnitude of lead contamination when comparing first-draw versus flushed water samples across each school district, and (2) the effectiveness of remediation measures when comparing time periods pre- and post-remediation. WLLs were mostly low, but some exceptionally high values skewed the distributions to the right.

3.1.1. WLL distributions at SPS school district

3.1.1.1. First-draw versus flushed water lead levels pre-remediation. First-draw WLLs across Seattle elementary schools ranged from 0.5 μg/L (minimum lead representing values below detection) to 1,600 μg/L (maximum lead detected at one elementary school) (Fig. 3a). The mean and median first-draw WLLs at SPS were 24.4 and 4.0 μg/L respectively, with the mean higher than the EPA guideline of 20 μg/L. Out of 1418 first-draw samples, 16% were below lead detection and 62% contained detectable lead but lower than the EPA guideline. The remaining 22% of first-draw samples exceeded the EPA guideline (Fig. 3a).

Flushed WLLs across Seattle elementary schools ranged from 0.5 μg/L (representing values below detection) to 370 μg/L (maximum lead detected at one elementary) (Fig. 3a). The median flushed WLL was 1.0 μg/L, whereas the mean flushed WLL was 3.4 μg/L. Out of 1418 flushed samples, 46% were below lead detection and 52% had detectable lead below 20 μg/L. The remaining 2% of flushed samples exceeded the EPA guideline, indicating hazardous taps at some schools even after flushing.

Flushed water contained on average ~60% less lead than first-draw water. This is consistent with the general expectation that flushing dilutes peak concentrations of lead, compared to first-draw stagnant water contained within end-point plumbing (Maas et al., 1994). A relatively "weak" correlation between first-draw and flushed WLLs in SPS elementary schools, with Spearman's rho = 0.634, indicated that fountains dispensing high lead in first-draw water did not necessarily dispense high lead in flushed water.

3.1.1.2. First-draw versus flushed water lead levels post-remediation. A broad range of voluntary remediation measures by the school district were effective, as illustrated by both lower first-draw WLLs and lower flushed WLLs (Fig. 3a). After remediation, first-draw WLLs ranged from 0.5 μg/L to 54 μg/L. More than half of first-draw samples were now below lead detection (53% versus 16% before remediation), and only a very limited number of samples still exceeded the EPA guideline of 20 μg/L lead (1% versus 22% before remediation). First-draw WLLs also had a much lower mean and median (2.1 and 0.5 μg/L respectively).

Flushed WLLs were also lower after remediation, with a mean and median of 0.7 and 0.5 μg/L. None of the flushed water samples exceeded 20 μg/L of lead after remediation. These benefits are attributable to the long-term measures undertaken by SPS, including installation of filters and removal of the lead sources (e.g., leaded piping and leaded bubbler heads). An even lower Spearman's rho correlation coefficient of 0.462 was obtained between first-draw and flushed WLLs post-remediation.

3.1.2. WLL distributions at LAUSD school district

3.1.2.1. First-draw versus flushed water lead levels. First-draw WLLs across LA elementary schools ranged between 0.2 μg/L and 13,000 μg/L (Fig. 3b). The mean and median first-draw WLLs at LAUSD were 11.0

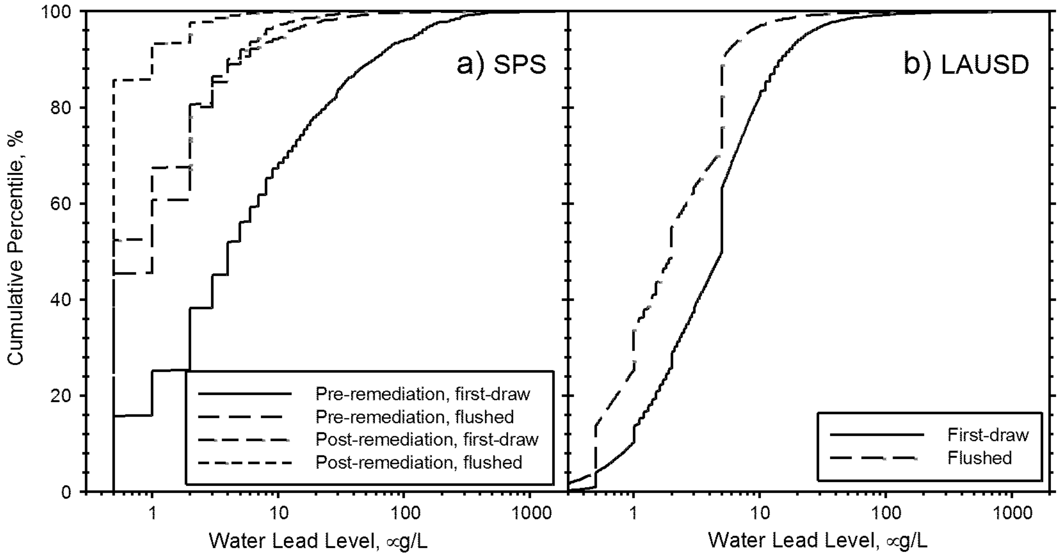

Fig. 3. Cumulative probability distributions of first-draw and flushed WLLs on a log-scale for a) SPS elementary schools as a whole, and b) LAUSD elementary schools as a whole.

and 5.0 μg/L respectively, with the mean lower than the EPA guideline. Out of 50,336 first-draw samples, 10% contained less than 1.0 μg/L lead, 84% contained lead between 1.0 and 20 μg/L, whereas 6% exceeded 20 μg/L.

Flushed WLLs ranged between 0.2 and 7400 μg/L, with a mean and median of 4.0 and 2.0 μg/L respectively (Fig. 3b). A Spearman's rho = 0.656 was calculated between first-draw and flushed WLLs across LA elementary schools, similar to Seattle's pre-remediation value.

Since LAUSD implemented voluntary remedial flushing of each water outlet by school staff (mostly janitors and teachers) every morning for 30 s, post-remediation was assumed to eliminate first-draw WLLs and included only the flushed WLLs (i.e., the modified Eq. (2) was used instead of Eq. (1)). As mentioned previously, this scenario represents a lower bound to actual exposure, given possible limitations of flushing in maintaining low WLLs throughout the school day. The reduction in WLLs after flushing was ~40% on average for LAUSD schools, lower than the ~60% average reduction after flushing for SPS schools pre-remediation. Since the effectiveness of flushing depends on the location of the lead source and the size of pipes leading from the source to the outlet, it is speculated that inherent differences in the plumbing lines of the two school systems resulted in different effects of flushing even though the same flushing protocol was followed. This suggests that ideally, fountain-specific flushing requirements backed up by sampling data would need to be developed, to ensure that the flushing time and frequency provide low lead water at a given school.

3.2. WLL school-to-school variability in SPS pre- and post-remediation

Significant variability in lead release was observed from school to school in both districts. To illustrate this variability, 3 representative schools across the SPS school district were selected based on their median pre-remediation first-draw WLL (Fig. 4). The "high exposure school" had a median first-draw WLL of 120 μg/L (based on N = 13 sampled faucets/fountains), the "typical exposure school" had a median first-draw WLL of 6 μg/L (N = 38), and the "low exposure school" had a median first-draw WLL of 0.5 μg/L (N = 19).

For the pre-remediation "high exposure school", first-draw WLLs were consistently high across school fountains (ranging 8–310 μg/L), but the combined exposure was "diluted" by lower flushed WLLs (ranging 1–51 μg/L) and by the lower 90th percentile home WLL of 10.3 μg/L in 2004 (see Eq. (1) for calculation of combined WLL distribution). The contribution of first-draw school WLLs was high enough to cause exceedance of the 20 μg/L school guideline in approximately 60% of water samples (i.e., combined WLL cumulative 40th percentile N 20 μg/L) (Fig. 4a). After remediation, both first-draw and flushed WLLs were lower and less variable (range 0.5–2 μg/L and 0.5–1 μg/L respectively), but the combined WLLs were slightly higher than that (Fig. 4b) due to the higher 90th percentile home WLL of 5.0 μg/L in 2011.

The pre-remediation "typical exposure school" exceeded the guideline in 6% of combined samples (i.e., combined WLL 94th percentile Q_{94} N 20 μg/L), and the "low exposure school" exceeded the guideline in 6% of combined samples as well (Fig. 4c, e). Unlike the "high exposure school", lead contamination of water in these two schools was not widespread, but limited to certain water outlets.

After voluntary remediation, all 3 SPS schools exhibited a similar behavior in terms of combined WLL exposure, with no exceedance of the 20 μg/L guideline at any percentile (Fig. 4b, d, f). The combined WLL exposures were almost constant across each school, as illustrated by almost vertical combined WLL curves (Fig. 4b, d, f). However, some remnant high first-draw WLLs created situations wherein students drinking water from certain fountains in the morning were exposed to high lead in water, even post-remediation (see first-draw curve in Fig. 4d). This suggests that water lead testing should be periodically repeated even after remediation, and SPS correctly decided to require water lead testing at its schools every three years (Boyd et al., 2008).

3.3. Background predicted risk of elevated blood lead from lead sources other than school water

Based on other default lead exposures assumed in the IEUBK model (air, soil, dust, diet), if the WLL was set to 0 μg/L for all water consumed (at home and at school), the resulting percent of students exceeding the 5 μg/dL BLL threshold would be 2.8% (Table 2). This is a background predicted risk to all students at all schools of SPS and LAUSD, representing BLL exceedance from non-water lead sources.

If just the school water was set to 0 μg/L, but the home water was set to the 90th percentile of the LCR, post-remediation exceedance of the 5 μg/dL BLL threshold for SPS would be 4.4% (Table 2). Similar simulations could be performed for LAUSD schools (Table 2). These express background risks to all students from air, soil, dust, diet and from home water lead, but not from school water lead. Any predicted risks above those background levels are attributable to school WLLs exclusively, in results presented in the following sections.

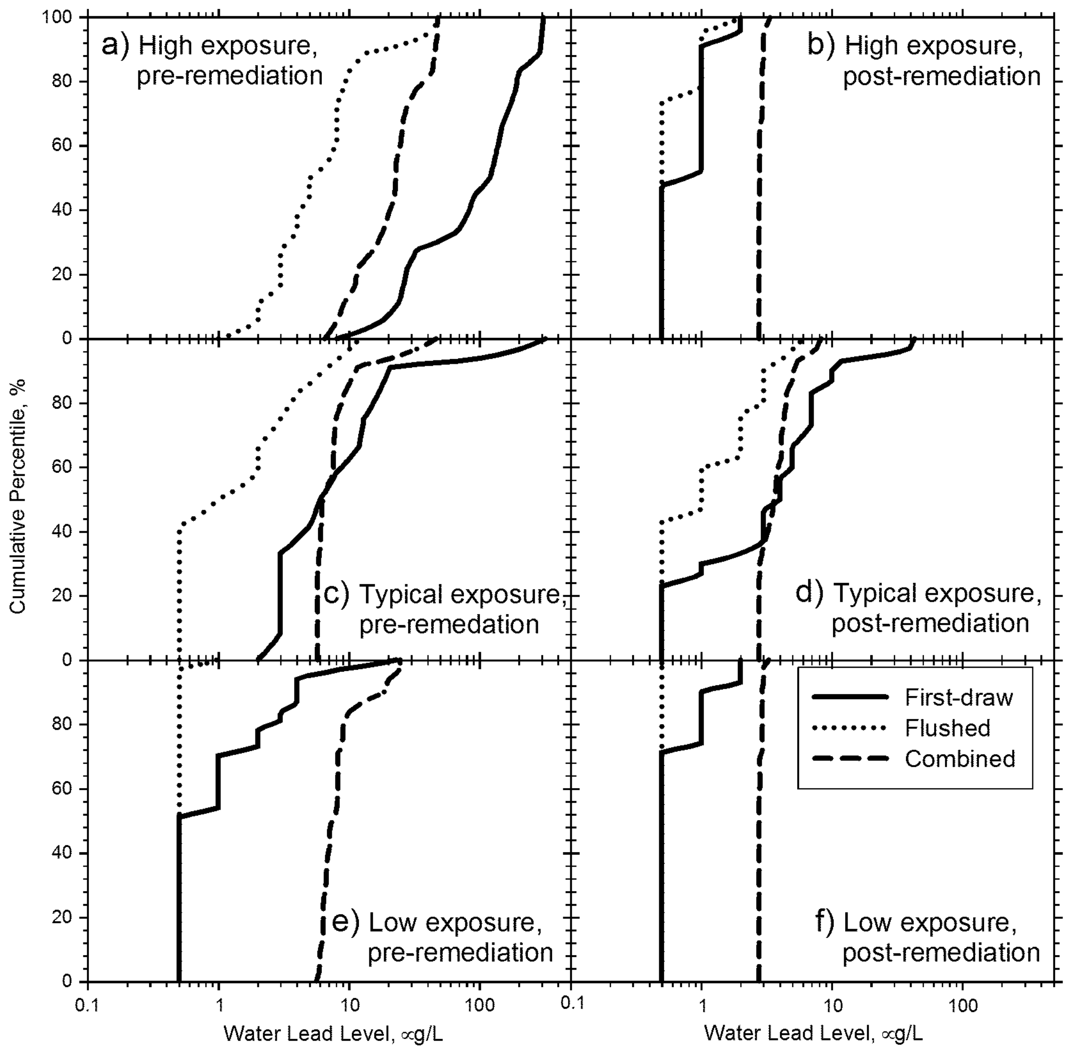

Fig. 4. Cumulative probability distributions of WLLs in three representative SPS elementary schools (classification criterion is pre-remediation first-draw median WLL): a) "high exposure school" pre-remediation, b) "high exposure school" post-remediation, c) "typical exposure school" pre-remediation, d) "typical exposure school" post-remediation, e) "low exposure school" pre-remediation, and f) "low exposure school" post-remediation.

3.4. Example of overall predicted risk of elevated blood lead in SPS "high exposure school"

3.4.1. Overall predicted risk of elevated blood lead

In the pre-remediation period, if water was routinely consumed at the 50%ile of the combined WLL distribution exposure at "high exposure school" (i.e., 22.8 μg/L in Fig. 4a), a child's predicted likelihood of having EBL based on a 5 μg/dL threshold was 29% (Fig. 5a). Likewise, exposure to the 90%ile WLL (i.e., 45 μg/L) corresponds to a 59% predicted likelihood of EBL, while exposure to the 99%ile WLL (i.e., 47 μg/L) corresponds to more than 60% predicted likelihood of EBL (Fig. 5a). At the old BLL reference value of 10 μg/dL, the respective population exceedance would be 2% at median water lead exposure, 10% at the 90%ile water lead exposure and 12% at the 99%ile water lead exposure (Fig. 5a).

By numerically integrating the area under each curve over the entire distribution of WLLs, the overall predicted risk of EBL (BLL N 5 μg/dL) for the students at "high exposure school" was calculated to be 31% pre-remediation (the light shaded area in Fig. 5a). This means that accounting for the whole range of WLL combined exposure at that given school and at home (and the other background lead sources), 31 out

Table 2
Background predicted risk of elevated blood lead in 5–6 year old students from non-school water lead sources, including air, soil, dust and diet.

Background predicted risk of elevated blood lead⁎	Children with BLL N 5 μg/dL	Children with BLL N 10 μg/dL
SPS and LAUSD (home and school WLL set to 0)	2.8%	b0.1%
SPS and LAUSD pre-remediation, including home WLL (school WLL set to 0)	6.4%	0.1%
SPS post-remediation, including home WLL (school WLL set to 0)	4.4%	b0.1%
LAUSD post-remediation, including home WLL (school WLL set to 0)	4.6%	b0.1%

WLL: water lead level; BLL: blood lead level; SPS: Seattle Public Schools; LAUSD: Los Angeles Unified School District.

⁎ Background air, soil, dust, and diet lead exposures kept constant at their IEUBK model default values.

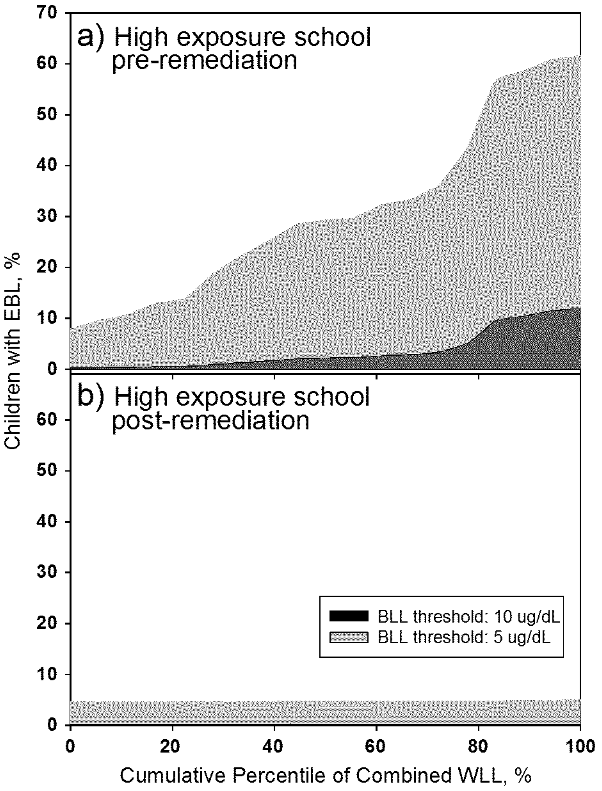

Fig. 5. Predicted percentage of children with EBL (i.e., BLL N 10 or N5 μg/dL) at distinct levels of water lead exposure observed in SPS "high exposure school" a) pre-remediation and b) post-remediation. Integration of the curves (i.e., calculation of highlighted area under the curves) estimates overall percent exceedances at the "high exposure school" depending on the chosen BLL threshold.

of 100 students were predicted to develop BLL N 5 μg/dL. For the threshold of 10 μg/dL the risk was 4% (the dark shaded area in Fig. 5a).

Post-remediation predictions were much lower than pre-remediation (Fig. 5b). Post-remediation, the overall risk to develop BLL N 5 μg/dL was calculated to be about 5% (the light shaded area in Fig. 5b), and the risk to develop BLL N 10 μg/dL was b0.1% (the dark shaded are in Fig. 5b). For comparison, recall that if the SPS school WLL was set to 0 μg/L, the corresponding exceedances would be almost identical at 4.4% and b0.1% (see Table 2). This suggests that voluntary remediation efforts at SPS "high exposure school" virtually eliminated school water as a source of lead. The remaining cases of EBL would need to be addressed by eliminating other assumed background lead sources in the children's environments, aside from school water lead.

The integration approach detailed for "high exposure school" (Fig. 5) was followed for all SPS and LAUSD elementary schools, and the integrated results (overall predicted risk of EBL) are summarized below.

3.5. Overall predicted risk of elevated blood lead in SPS elementary students

The contribution of combined WLLs (see illustrative combined distributions in Fig. 4) to EBL was assessed by comparing the overall predicted risk of elevated blood lead (EBL) at each school before and after remediation of water lead problems. All 63 SPS elementary schools fell below the 1:1 reference line after water remediation (Fig. 6a) indicating that overall risk of EBL was reduced in all schools post-remediation.

3.5.1. Predicted percentage of students with BLL N 10 μg/dL

The percentage of school children exceeding that threshold at "high exposure school" dropped from 4% pre-remediation to b0.1% post-remediation (red circle in Fig. 6a), as previously illustrated in detail (Fig. 5a and b). The "typical exposure school" dropped from 0.6% exceedance to 0.1% after WLL remediation, whereas the "low exposure school" dropped from 0.2% exceedance to b0.1% after remediation (red circles in Fig. 6a).

3.5.2. Predicted percentage of students with BLL N 5 μg/dL

The percentage of school children exceeding that threshold at the "high exposure school" dropped from 31% pre-remediation to about 5% post-remediation (red triangle in Fig. 6a). The "typical exposure school" dropped from 11% exceedance to about 5% after WLL remediation, whereas the "low exposure school" dropped from 7% exceedance to about 5% after remediation (red triangles in Fig. 6a).

Clearly, the extent of the public health benefit was dependent on the initial extent of the water lead problem, and worst-case schools (like "high exposure school") benefited the most from remediation efforts. However, regardless of the extent of the problem (remember differences in WLLs between "high exposure school", "typical exposure school" and "low exposure school" from Fig. 4), water lead remediation

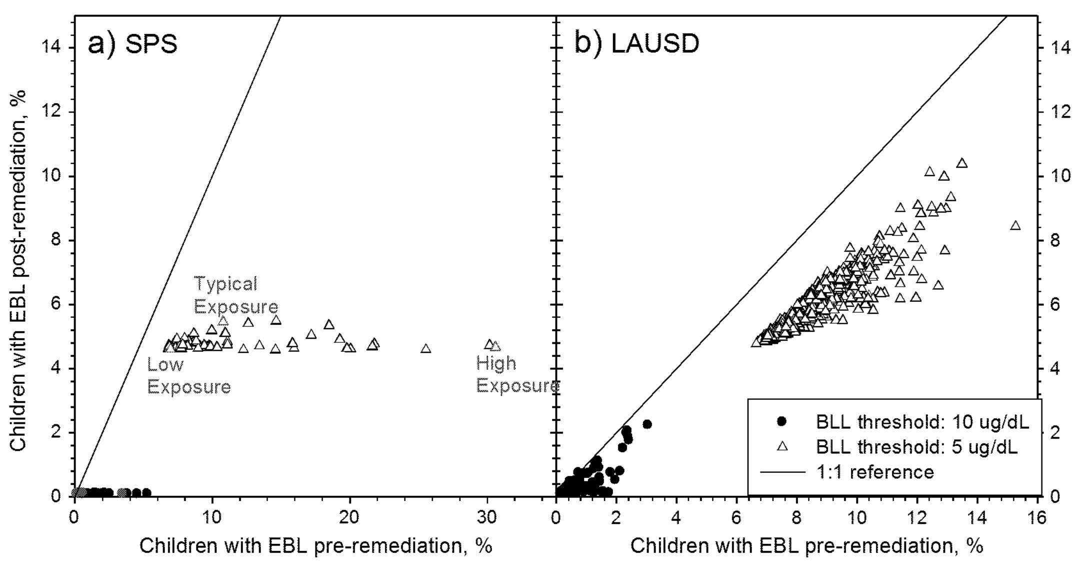

Fig. 6. Percentage of children with elevated blood lead (exceeding 10 μg/dL or 5 μg/dL) before and after remediation of water lead problems at a) each of 63 SPS elementary schools, and b) each of 601 LAUSD elementary schools. Data points highlighted with the color red are corresponding to three representative SPS schools that are discussed in detail. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

had a quantifiable predicted health benefit for at least a percentage of children attending classes at all SPS elementary schools.

As expected, halving the BLL safety criterion from 10 to 5 μg/dL increased the percentage of children that were potentially affected by water lead contamination (see extent of shaded areas for the "high exposure school" in Fig. 5). The % of students predicted to develop EBL are those consistently drinking from high-risk fountains at a given school (i.e., upper tail of the combined WLL model input, see Fig. 4), and students who are more sensitive than others to the same lead dose, based on the IEUBK model's probability component (see upper tail of BLL distribution in Fig. 1).

Similarly to the "low exposure school", the "typical exposure school" and the "high exposure school", all other SPS elementary schools were predicted to have a similar 4.6–5.5% overall risk of exceeding the new BLL reference value after remediation (Fig. 6a). The background percentage of EBL is 2.8% if overall WLL of 0 μg/L was consumed, and 4.4% if only school WLL was reduced to 0 μg/L (see Table 2). This suggests that the predicted percentage of EBL after WLL school remediation was largely controlled by other background lead exposures in the students' environments from soil, air, dust and diet (which were assumed fixed at their model default values) and by the home WLLs.

3.6. Corresponding number of SPS elementary students with elevated blood lead

3.6.1. Corresponding number of students with predicted BLL N 10 μg/dL

Student enrollment in 2010–2011 at "high exposure school" was 414 (Seattle Public Schools, 2011). Therefore 4% of students would translate to 17 students with EBL pre-remediation, and that number dropped to 1 student post-remediation, indicating a predicted major health benefit for 16 students.

This conclusion does not contradict the analysis of Sathyanarayana et al. (2006), which also assessed health risks to Seattle students from water exposure at SPS schools pre-remediation. That work predicted low geometric mean BLLs (b5 μg/dL) in students of all Seattle schools, and thus suggested that in Seattle, elevated school drinking water lead concentrations were not a significant source of lead exposure in school-age children. That conclusion is valid for the typical student and typical WLL exposure, when excluding the tail of the WLL and BLL distributions. Consideration of the upper tail of the BLL and WLL distributions (as was done herein) yielded additional conclusions in terms of %EBL.

3.6.2. Corresponding number of students with predicted BLL N 5 μg/dL

Student enrollment in 2010–2011 at the "typical exposure school" was 368, at the "low exposure school" was 376, and at the "high exposure school" was 414 (Seattle Public Schools, 2011). If the predicted %EBL (i.e., % of students with BLL N 5 μg/dL) is translated to actual student populations, the "typical exposure school" had an estimated 40 students with predicted EBL pre-remediation, and an estimated 20 students with EBL post-remediation. Therefore water lead remediation efforts were predicted to have a major estimated health benefit to about 20 students (40 - 20 = 20), on a relative pre- versus post-remediation basis.

Similar calculations for the "high exposure school" suggest that 128 students had EBL pre-remediation, whereas that number dropped to 21 students post-remediation (major health benefit to 107 students). For the "low exposure school", 26 students were predicted to develop EBL pre-remediation, whereas 17 students were predicted to develop EBL post-remediation (major health benefit to 9 students).

The vast majority of post-remediation students with predicted EBL at the 3 SPS schools were due to lead exposure outside of school drinking water (16 out of 17 students for "low exposure school", 16 out of 20 students for "typical exposure school", and 18 out of 21 students for "high exposure school"), based on the background 4.4% predicted risk if school WLL was set to 0 μg/L (see Table 2).

Since any model has limitations that restrict the certainty of the absolute predictions, these numbers can be viewed as rough approximations of the actual number of students with EBL.

3.7. Overall predicted risk of elevated blood lead in LAUSD elementary students

All LAUSD elementary schools fell below the 1:1 reference line, indicating that the voluntary remedial measure of flushing would reduce risk from combined water lead exposure in all 601 elementary schools (Fig. 6b). Since most data points fell just below the 1:1 line (Fig. 6b), the predicted health benefit from implementing remedial flushing was not as pronounced as in Seattle (Fig. 6a), which remediated through installation of water filters and replacement of lead plumbing sources (problematic fountains/piping).

3.7.1. Predicted percentage of students with BLL N 10 μg/dL

All 601 LAUSD elementary schools had b3% risk of students to exceed the BLL reference value of 10 μg/dL pre-remediation (Fig. 6b). After remediation, students in all schools had b2.2% chance to exceed the BLL (Fig. 6b).

3.7.2. Predicted percentage of students with BLL N 5 μg/dL

All elementary schools had a 7–16% risk of students to exceed the BLL threshold pre-remediation, and that percentage dropped to 5–11% post-remediation (Fig. 6b). For the "highest-risk" school, EBL exceedance dropped from 15% pre-remediation to 8% post-remediation (Fig. 6b, triangle data point furthest to the right). For the "lowest risk" school it dropped from 7% to 5% (Fig. 6b, triangle data point furthest to the left). Student enrollment statistics were not available for LAUSD schools, so the corresponding number of students benefiting from these estimated risk reductions could not be calculated.

The percentage of students with EBL in most LAUSD schools after remediation (Fig. 6b) was higher than the percentage of students with EBL in all SPS after remediation (Fig. 6a). As a reminder, any BLL exceedance above the background level of 2.8% (attributable to other background lead sources and 0 WLL) is due to WLLs at home and at school, and any BLL exceedance above 4.6% is attributable to school WLL exposure for LAUSD students.

3.8. Mean predicted risk of elevated blood lead in SPS elementary students

After presenting individual school results (Fig. 6), the mean predicted risk of EBL across all schools for the entire school district was calculated (Fig. 7).

3.8.1. Mean predicted percentage of SPS students with BLL N 10 μg/dL

If individual school results are averaged for all 63 SPS elementary schools pre-remediation, 0.8% of students were predicted to exceed BLL of 10 μg/dL on average. This percentage was reduced to b0.1% of students post-remediation, whereas this percentage would be b0.1% if all water consumed contained 0 μg/L of lead (Fig. 7a, top).

3.8.2. Mean predicted percentage of SPS students with BLL N 5 μg/dL

If individual school results are averaged for all 63 SPS elementary schools pre-remediation, 11.2% of students were predicted to exceed BLL of 5 μg/dL pre-remediation. This percentage was reduced to 4.8% of students post-remediation, whereas this percentage would be 2.8% if all water consumed contained 0 μg/L of lead (Fig. 7a, bottom). If the upper 75% of SPS schools were taken into account (N = 16 schools with the highest WLL exposure), the mean percentage of children will EBL pre-remediation was predicted at 19.5% pre-remediation, and was reduced to 4.8% on average post-remediation (Fig. 7a, bottom).

This suggests that after remediation efforts, SPS schools that were initially "worst-case" dropped to the same low predicted level of risk,

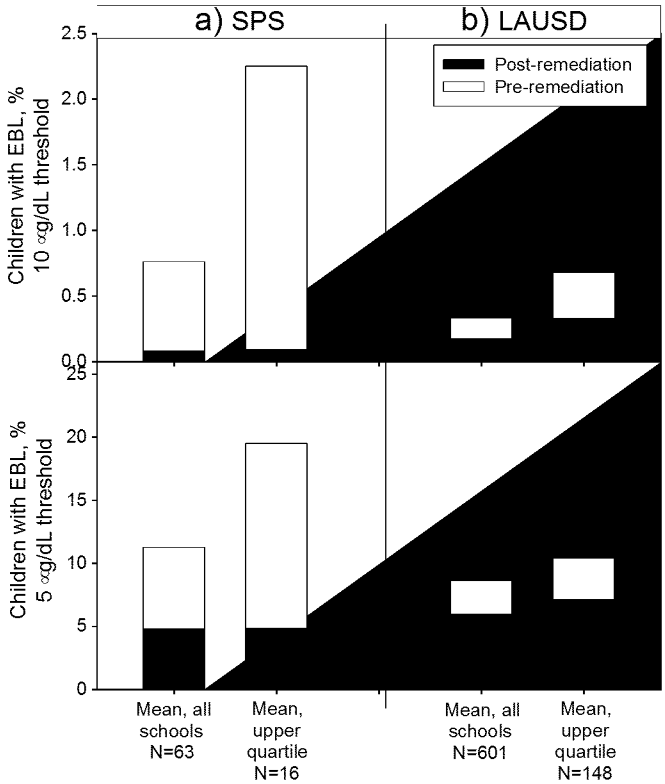

Fig. 7. Mean percentage of children with elevated blood lead (exceeding 10 µg/dL or 5 µg/dL) before and after remediation of water lead problems at a) SPS elementary schools, and b) LAUSD elementary schools.

as the rest of the school district. Prior to remediation, averaging risks across school districts (11.2% risk to exceed 5 µg/dL of BLL) would tend to mask larger problems at that upper 75% of "worst-case" schools (19.5% risk) (Fig. 7a, bottom).

3.9. Mean predicted risk of elevated blood lead in LAUSD elementary students

3.9.1. Mean predicted percentage of LAUSD students with BLL N 10 µg/dL

If individual school results are averaged for all 601 LAUSD elementary schools pre-remediation, 0.3% of students were predicted to exceed BLL of 10 µg/dL on average. This percentage was reduced to 0.2% of students post-remediation, whereas this percentage would be b0.1% if all consumed water contained 0 µg/L of lead (Fig. 7b, top). If the upper 75% of SPS schools were taken into account (N = 148 schools with the highest WLL exposure), the mean percentage of children with EBL pre-remediation was predicted at 0.7% on average, and was reduced to 0.3% on average post-remediation (Fig. 7b, top).

3.9.2. Mean predicted percentage of LAUSD students with BLL N 5 µg/dL

If results are averaged for all individual 601 SPS elementary schools pre-remediation, 8.6% of students were predicted to exceed BLL of 10 µg/dL on average. This percentage was reduced to 6.0% of students post-remediation, whereas this percentage would be 2.8% if all water consumed contained 0 µg/L of lead (Fig. 7b, bottom). If the upper 75% of SPS schools were taken into account (N = 148 schools with the highest WLL exposure), the mean percentage of children will EBL pre-remediation was predicted at 10.4% on average, and was reduced to 7.1% on average post-remediation (Fig. 7a, bottom).

3.10. Limitations

3.10.1. SPS and LAUSD water lead datasets

Reasonable attempts were made to remove from the original datasets schools that were temporary, closed, relocated, or were inconsistent with the age criteria developed for filtering, but errors cannot be completely ruled out. Several of the closed schools also had very high WLLs, and the reduced exposure achieved by closing these schools was not included in this analysis. Assessing seasonal variation in water lead levels was outside the scope of this work. Other modeling work (Deshommes et al., 2013) has found it important in children's IEUBK simulations, and proposed that blood lead studies be conducted in the summer to detect seasonal exceedances.

3.10.2. Modeling assumptions

As discussed, default (i.e., not site-specific) values for non-water lead exposures (from air, soil, dust, and diet) were assumed in the model both before and after remediation of water lead at the schools. These default inputs affected predicted values, but had limited impact on the predicted health improvements estimated on a relative pre- versus post-remediation basis (they were kept constant both before and after remediation of water lead).

Daily water consumption was assumed fixed at 0.58 L/day (the model's default value for 5–6 year old children), and a possible distribution of water intake among different children was not considered.

Home water lead exposure was assumed to comprise the 90th percentile LCR lead level measured at Seattle and Los Angeles homes by the local water utilities, because other home data were not available. The 90th percentile LCR water lead level tends to overestimate water lead exposure at home (as opposed to a 50th percentile home WLL or other lower percentiles that drinking water utilities are not required to report). Even so, it "diluted" the even higher water lead exposure at "high risk" LAUSD and SPS schools pre-remediation, and therefore reduced the relative predicted benefits of school water remediation.

Implementation of flushing at LAUSD is difficult to verify. In addition, Murphy (1993) reported that lunch-time water samples in New Jersey schools contained significantly higher lead levels than morning flushed samples. As a result, periodic flushing several times per day (not just once per day) might be required at schools to ensure consistently low lead levels (Murphy, 1993). To the extent that LAUSD school staff were not consistently performing daily flushing at LAUSD, or if flushing time (30 s) and frequency (once per day) were not sufficient to keep WLLs low throughout the school day as was the assumption here, fewer health benefits would be expected, and higher percentages of students would have EBL than those predicted.

4. Conclusions

Both SPS and LAUSD elementary schools had water fountains dispensing variable levels of lead in water (SPS range in 2004: b1–1600 µg/L in first-draw water, b1–370 µg/L in flushed water; LAUSD range in 2008–2009: 0.2–13,000 µg/L in first-draw water, 0.2–7400 µg/L in flushed water). The wide range in children's water lead exposure reinforces the need to sample all water fountains at schools, as was done in SPS/LAUSD and as is recommended by the US EPA under the LCCA. Sampling a limited number of school outlets and extrapolating results to the remaining un-sampled school taps assume that lead levels in school water are uniform, when they tend to be variable. Factors contributing to variable lead release from plumbing into drinking water have been described elsewhere (Triantafyllidou and Edwards, 2012; Schock and Lemieux, 2010). While desirable, if sampling all water outlets is not feasible at large schools, then targeted sampling of water outlets that are more commonly used by students should be a priority (e.g., water fountains rather than bathroom faucets), and those results should not be extrapolated to remaining un-sampled outlets.

School fountains at SPS and LAUSD were dispensing elevated WLLs even if the respective local water utilities were compliant with the federal lead action limit for home taps. Compliance with the federal LCR does not necessarily imply elimination of water lead problems at schools.

LAUSD students across 601 schools had an average predicted risk of 8.6% to exceed BLL N 5 μg/dL pre-remediation, and that percentage dropped to 6.0% post-remediation. Remediation by flushing was therefore an improvement, but it was unable to reduce the risk of EBL to levels as low as in SPS (from 11.2% to 4.8% on average across 63 SPS schools). This is in part because of more active remediation measures in SPS (replacement of fountains/piping, and installation of filters).

Predicted risks at individual SPS schools varied pre-remediation (7% risk of BLL N 5 μg/dL at a "low exposure school", 11% risk at a "typical exposure school", and 31% risk at a "high exposure school"). Predicted risks in these 3 schools after remediation dropped to 4.6–5.4%, and only the percentage greater than the background 4.4% risk is attributable to school WLLs. Based on student enrollment information, risk reduction translated to an estimated major public health benefit for 107 students attending classes in the "high exposure school", 20 students attending classes in the "typical exposure school", and 9 students attending classes in the "low exposure school". All modeling results were based on certain modeling assumptions, and it is recognized that different assumptions would yield different results. Even so, predicted health improvements were estimated on a relative pre- versus post-remediation basis, for which the modeling assumptions remained the same.

Overall, SPS and LAUSD tested for and remediated water lead problems on a voluntary basis, and this is the first attempt to assess the public health benefits. Despite the fact that high levels of lead were detected and caused negative publicity and parental concern in the short-term, these two case studies exemplify good practice.

In an era with increasingly stringent public health goals (e.g., reduction of BLL safety threshold from 10 to 5 μg/dL), the predicted health benefits in the blood lead level of high-risk students (more sensitive or more exposed as expressed by the predicted % of student population with EBL) are quantifiable and important. School water lead remediation efforts are therefore significant in reducing health risks to US elementary students.

Conflict of interest

The authors do not have any conflict of interest.

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